The Daya Bay Experiment and the Quest for θ_{13}

David E. Jaffe for the Daya Bay Collaboration

Why θ_{13}?

$|\nu_f\rangle = \sum_i U^*_{fi}|\nu_i\rangle$ Interaction eigenstates $\neq$Mass eigenstates

$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$

$$U_{if} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \approx 45^\circ$
Atmospheric ν
Accelerator ν

$\theta_{13} < 10^\circ$
Short-baseline Reactor ν
Future accelerator ν

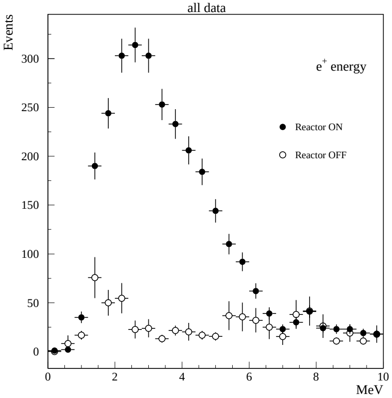
$\theta_{12} \approx 35^\circ$
Solar ν
Long-baseline Reactor ν

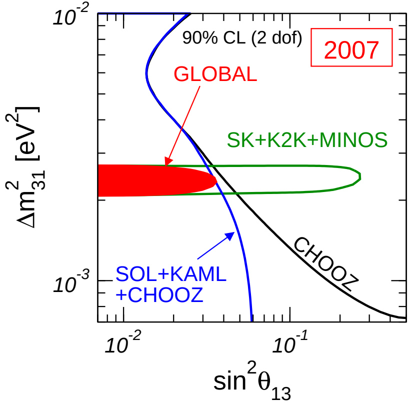
$$\boxed{\text{Daya Bay design sensitivity: } \sin^2 2\theta_{13} < 0.01 \text{ (90\%CL)}}$$

Short-baseline Reactor $\bar{\nu}_e$ is a disappearance experiment:

$$\mathcal{P}(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E)$$

Chooz: Best experimental limit on θ_{13}

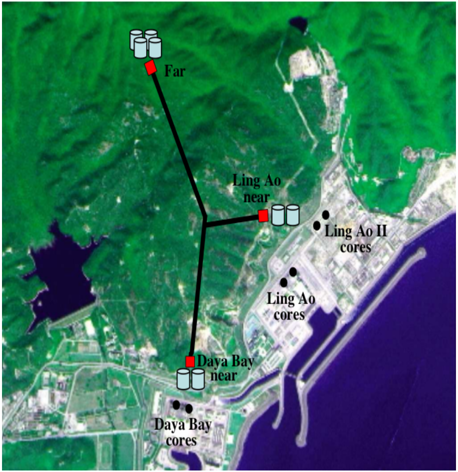




5 ton target exposed to 2 reactors, total thermal power 8.5 GW, 1 km baseline
Phys.Lett.B**466** (1999) 415

Recent global ν analysis
`arXiv:0710.5027`

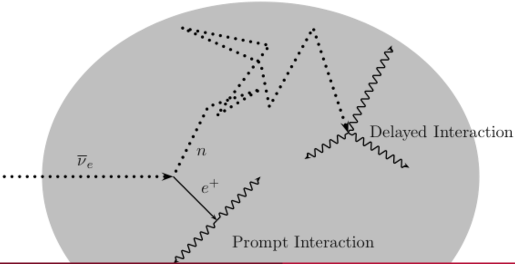
Getting to $\sin^2 2\theta_{13} < 0.01$

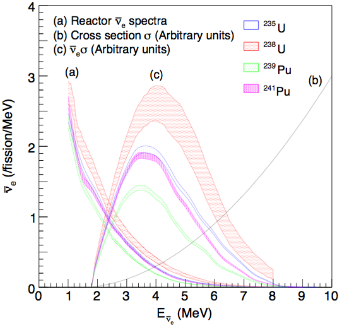


- *Increase statistics:* $4\times$ 20 ton target at far site, 11.6 $\mathrm{GW_{th}}$ (17.4 $\mathrm{GW_{th}}$ in 2011). $1\ \mathrm{GW_{th}} = 2 \times 10^{20} \bar{\nu}_e/\mathrm{s}$
- *Suppress cosmogenic background:* Go deeper.
- *Reduce systematic uncertainties:* Deploy "identical" near/far detector pairs.
- *Optimize baseline*

$\bar{\nu}_e$ detection method

- Inverse-beta decay: $\bar{\nu}_e p \longrightarrow e^+ n$
- Target: 0.1% Gd-loaded Liquid Scintillator
  $nGd \longrightarrow Gd^* \longrightarrow Gd + \gamma s(8\ \mathrm{MeV})$
- $\sim 30\mu s$ mean neutron capture time
- Delayed coincidence provides powerful background rejection

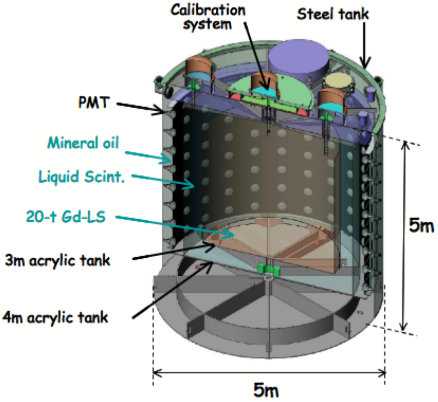




Reactor anti-neutrino spectrum

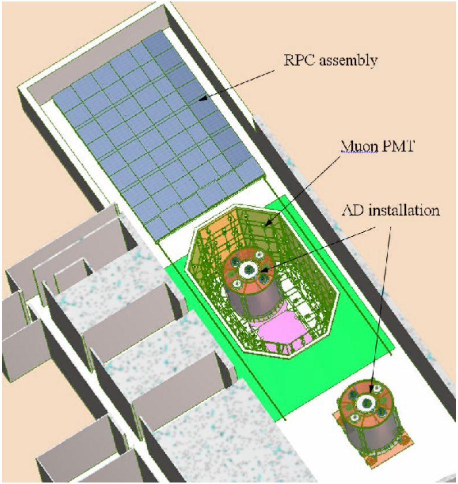
Anti-neutrino Detectors (ADs)

- 8 identical detectors: Reduce systematic uncertainties
- Each detector 3 nested cylinders:
  1. Inner: 20t GdLS [a] (d=3m)
  2. Mid: 20t LS [b] (d=4m)
  3. Outer: 40t mineral oil (d=5m
- 192 8-inch PMTs/detector
- Top/bottom reflectors
- Provides $12\%/\sqrt{E(\mathrm{MeV})}$ energy resolution



[a] GdLS=Gd-loaded Liquid Scintillator
[b] LS=Liquid Scintillator

Cosmic veto and shielding



- Multiple muon veto detectors
- Water Čerenkov
  - ADs submerged in water ($\geq 2.5\mathrm{m}$ shielding)
  - Inner/Outer regions optically separated by Tyvek sheets
  - 8-inch PMTs on frames (289/near, 384/far site)
- RPC: Provides independent veto above water pool

Reducing systematic uncertainties

Detector Uncertainty Source		Baseline	Goal	Chooz Experience
Number of protons		0.3%	0.1%	0.8%
Detection Efficiency	Energy cuts	0.2%	0.1%	0.8%
	H/Gd ratio	0.1%	0.1%	1.0%
	Time cut	0.1%	0.03%	0.4%
	Neutron mult.	0.05%	0.05%	0.5%
	Trigger	0.01%	0.01%	0.01%
	Live time	$< 0.01\%$	$< 0.01\%$	$< 0.01\%$
Total Uncertainty		0.38%	0.18%	1.7%
		Two detector **relative** uncertainty		One detector **absolute** uncertainty

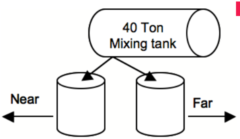
Requirements on systematic uncertainties

$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm f}}{L_{\rm n}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\frac{\mathcal{P}(L_{\rm f}, E; \sin^2 2\theta_{13})}{\mathcal{P}(L_{\rm n}, E; \sin^2 2\theta_{13})}$$

Measured ratio of rates

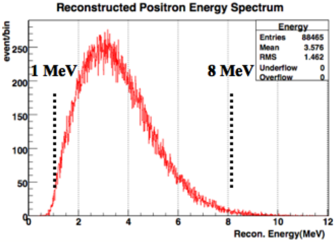
Number of protons

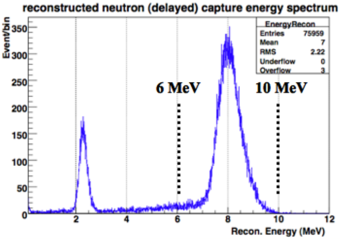
Efficiency ratio



- Attain $\leq 0.3\%$ on proton ratio by monitoring filling mass with load cells(accuracy $< 0.02\%$) and Coriolis mass flowmeters(accuracy $< 0.1\%$). Fill ADs in pairs.
- Attain $\leq 0.2\%$ on efficiency ratio with calibration

Detector efficiency





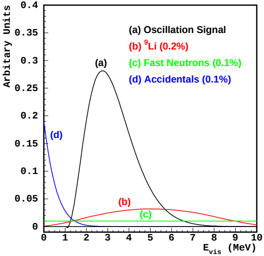
Simulation: Achieving 0.2% eff'y systematic, implies knowing e^+ threshold to 2% (easy) and relative neutron threshold to 1% (more difficult)

- Positron energy cuts at 1 & 8 MeV. Calibrate e^+ threshold with ^{68}Ge source.
- Neutron capture energy cut at 6 MeV. Calibrate with spallation nGd capture over full fiducial volume + weekly deployment of AmC source on 3 vertical axes.

Background processes and rates

Background due to natural radioactivity & cosmic ray interactions

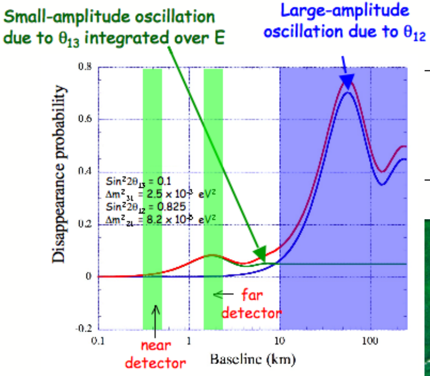
1. Muon interactions in the LS produce $^{9}\mathrm{Li}/^{8}\mathrm{He}$. A β^-, *n* emitter with Q=13 MeV, τ=0.178s. Expect bkgd/signal ~0.003. Can be measured with data (NIMA**564**(2005)081801).
2. Muon interactions outside AD in water and rock produce "fast" neutrons that interact in GdLS, LS. Expect bkgd/signal ~0.001. Can estimate rate from data and simulation.
3. Accidental coincidences of radioactive background with cosmogenic background. Expect bkgd/signal ~0.003. Calculable from observed singles rates.



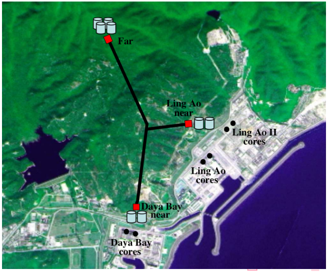
Oscillation signal for $\sin^2 2\theta_{13} = 0.01$

Optimize baseline

$$1 - \mathcal{P}(\bar{\nu}_e \to \bar{\nu}_e) = \sin^2 2\theta_{13} \sin^2 \frac{1.27\Delta m^2_{31} L}{E} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{1.27\Delta m^2_{21} L}{E}$$

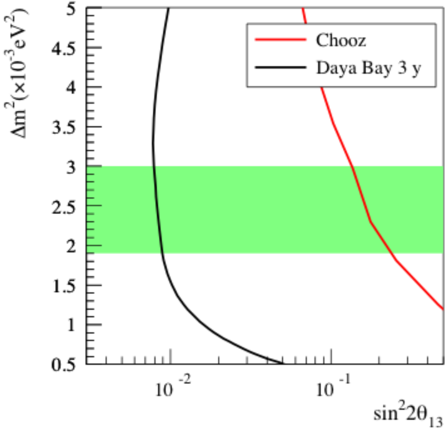


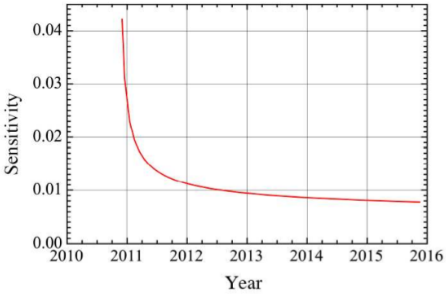
	Expt'l site		
Reactors	DyB	LA	Far
DayaBay	363	1348	1986
LingAo I	857	481	1618
LingAo II	1307	526	1613
Overburden	98	112	355



Expected sensitivity

90% CL limit on $\sin^2 2\theta_{13}$ assuming baseline systematics

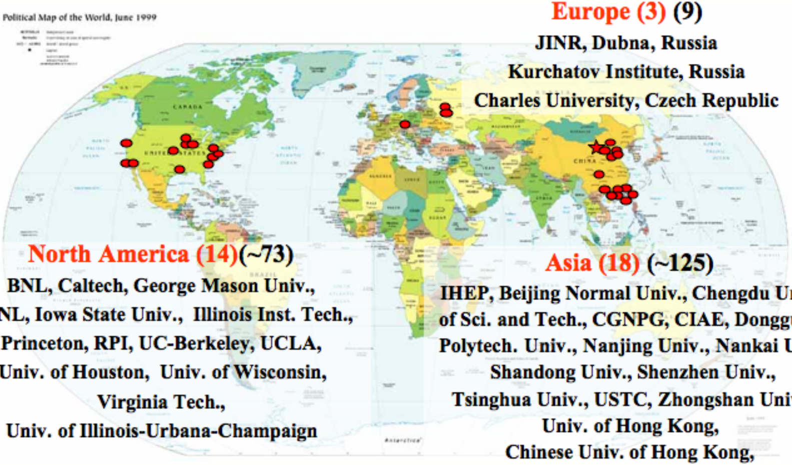




$$\Delta m^2 = 0.0025 \text{ eV}^2$$

3 years of data

The Daya Bay Collaboration



Europe (3) (9)

JINR, Dubna, Russia
Kurchatov Institute, Russia
Charles University, Czech Republic

North America (14)(~73)

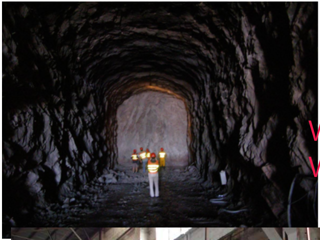
BNL, Caltech, George Mason Univ., LBNL, Iowa State Univ., Illinois Inst. Tech., Princeton, RPI, UC-Berkeley, UCLA, Univ. of Houston, Univ. of Wisconsin, Virginia Tech., Univ. of Illinois-Urbana-Champaign

Asia (18) (~125)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., Nanjing Univ., Nankai Univ., Shandong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

~207 collaborators

Status



Nov07	Began civil construction
Aug08	CD-3b Approval
Mar09	Occupancy of onsite assembly building
Winter09	Install AD pair in Daya Bay near site
Winter10	Begin data taking with near and far sites

Other physics with Daya Bay

Possible non-θ_{13} topics

1. $\bar{\nu}$ decay (appearance measurement)
2. CPT violation via sidereal variations in IBD rate
3. atmospheric ν and upward-going muons
4. supernova detection
5. precise determination of reactor spectrum
6. neutron (and alpha) emission after μ^- capture: multiplicity and/or energy spectra
7. measurement of muon spallation products at three depths
8. cosmic ray air showers
9. cosmic muon charge ratio

The last slide

- The Daya Bay Reactor Neutrino Experiment will be able to provide the most accurate measurement of $\sin^2 2\theta_{13}$ in the next few years.
- The experiment is being funded. Civil construction and detector fabrication is progressing.

See hep-ex/0701029 for more details.

Many thanks to my Daya Bay collaborators for their help in preparing this presentation.

Extra

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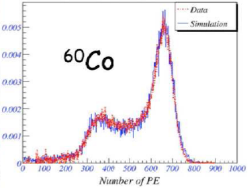
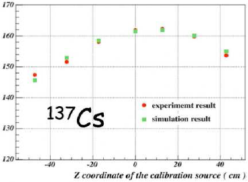
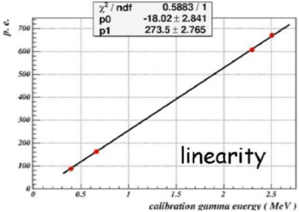
Prototype Antineutrino Detector Performance

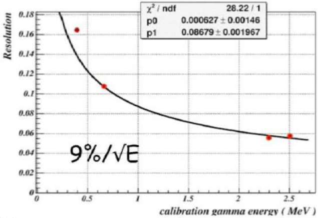
2-zone Prototype at IHEP

- 0.5 ton unloaded LS
- 45 8" PMTs with reflecting top and bottom



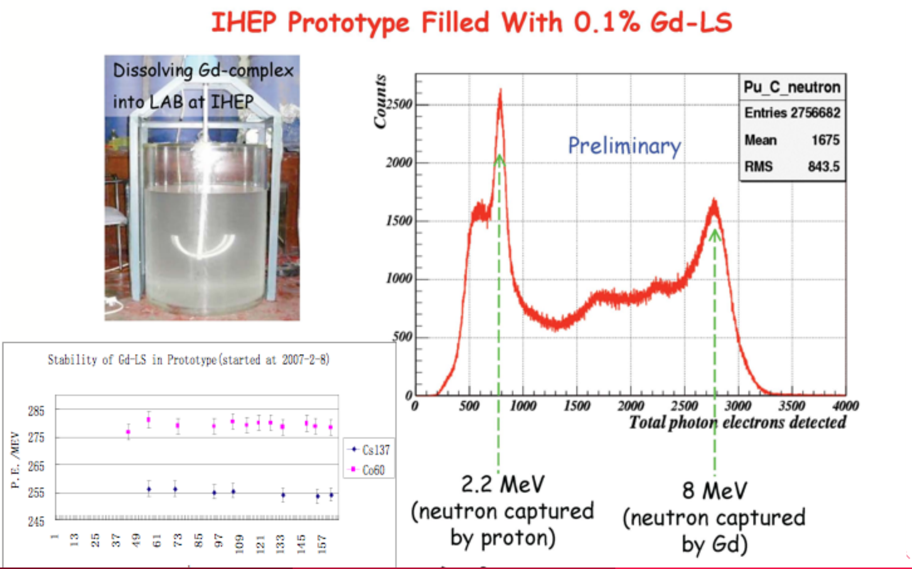






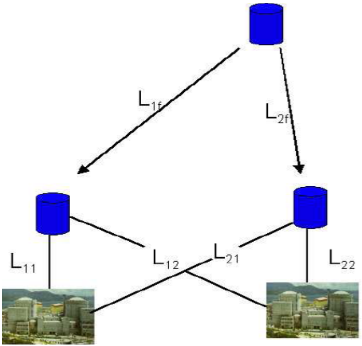
Kam-Biu Luk   Daya Bay   22

Prototype filled with 0.1% GdLS



Q: Cancellation $\bar{\nu}_e$ flux uncertainty with multiple reactor sites?

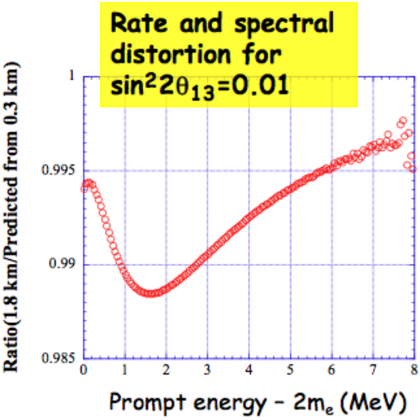
A: Deweight the oversampled cores by a factor α:
$\mathrm{Ratio} = \alpha \frac{\mathrm{Near1}}{\mathit{Far}} + \frac{\mathit{Near2}}{\mathit{Far}}$

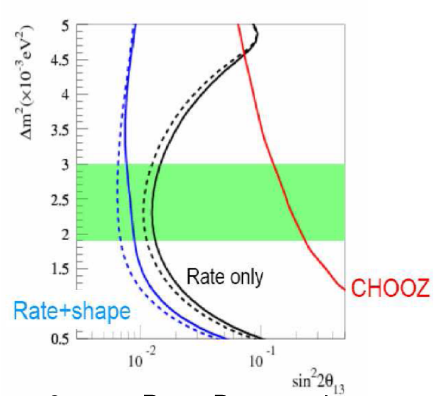


$$\alpha = \frac{(L_{22}^2 L_{1F}^2)^{-1} - (L_{21}^2 L_{2F}^2)^{-1}}{(L_{11}^2 L_{2F}^2)^{-1} - (L_{12}^2 L_{1F}^2)^{-1}}$$

For 4(6) cores, $\alpha = 0.34(0.39)$ and 2% reactor flux uncertainty is reduced to 0.035% (0.1%). Slightly more complicated expression if flux/reactor differs.

Sensitivity of rate and shape analyses





3 years Daya Bay running
Solid: 0.38% baseline syst. unc.
Dashed: 0.18% goal syst. unc.